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TOPICAL REVIEW

An update on engineering issues concerning stratospheric aerosol injection for geoengineering

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Abstract

Solar Radiation Management (SRM) geoengineering is a proposed response to anthropogenic global warming (AGW). Stratospheric aerosol injection (SAI) is one proposed method, reliant on lofting material into the stratosphere. Engineering reviews related to this technology approach have been sparse, with most major primary analyses now at least five years old. We attempt to bridge this gap—with a short, qualitative review of recent developments in various fields of engineering that have potential applicability to SAI. Our analysis shows that a new conventional aircraft design is still likely to be the most dependable and affordable technology solution (cost estimates start around \$1000–1500 per ton lofted), with hybrid or vacuum airships a potential challenger. Rockets, gas guns and MAGLEV/coilguns show some potential—although they lack the inherent level-flight capability that would be needed for direct aerosol distribution (versus distribution of gaseous precursors), without substantial additional engineering. Should very high-altitude access be required, rockets, jet-hybrid rockets, and various guns (especially light-gas guns) potentially offer the required capability. Costs and performance for tethered balloons remain highly uncertain. Towers are not found to be promising. The extreme accessibility of free balloons suggests that this method may be used primarily for reasons of political leverage, as opposed to being an optimal engineering solution.

Introduction

SAI geoengineering encompasses a variety of proposed engineering approaches [1]. These are designed to place particulates (or their precursor gases) into the upper atmosphere, for the purposes of reflecting solar radiation. The degree of intellectual effort expended in investigating engineering aspects of the discipline has been very minor, compared to that expended on earth system and governance aspects. Two influential reports have been produced on the costs and approaches available for lofting, and one less well-publicised analysis. While other, more specialist investigations have been carried out from time to time, only the NAS report from 1992 [2], the Aurora flight services report [3] and the lesser-known Davidson *et al* [4] (both of 2012) have attempted to systematically review the engineering approaches available. A later re-analysis looked chiefly at the existing papers, as opposed to appraising the technical progress in related fields [5]. As approaching a decade has passed since these various reports, there is a need for an update. This is particularly the case, considering the very rapid general progress that has been made in some related fields, during this time (hereinafter referred to as 'the quiet period'). Only one other paper, by Smith and Wagner [6], has been recently published that attempts a comprehensive review function, and this overlooked a wide range of potentially applicable technologies, as well as the potential need for higher altitude access [7, 8].

In this short paper, we provide a brief and principally-qualitative review of the advancing engineering fields applicable to stratospheric aerosol injection. Our purpose is not to provide robust cost estimates—but rather to horizon-scan for present engineering advances, which have the potential to provide major costs reductions, or technology improvements.

Usefully-quantitative cost estimates require some degree of technological maturity, on which to base rough designs. Cost estimates can thus only usefully be made for delivery by aircraft—where there has been sufficient preliminary design effort on which to base an estimate. These estimates start from \$1000 per ton (Moriyama *et al*), and include \$1400 per ton (Smith and Wagner, Bingaman *et al*), and also a wider range that starts at around \$1000 per ton and increases dependent on design requirements (Janssens *et al* 2020). For context: reducing global mean temperature by a modest 0.5 °C might require approximately 5 Mt SO_2/yr to be delivered to the stratosphere (Kravitz *et al* 2017); however, climate sensitivity is presently uncertain. The convergence of aircraft cost estimates among recent studies should not be assumed to reflect high confidence, given that no similar aircraft exist. Nevertheless, this range of costs provides context to the later discussion of other technologies, notwithstanding the lack of reliable cost estimates for these.

We note a diversity of potential technology approaches from the original reports, and additionally the heterogeneous cost estimates provided therein. The nature of engineering is that it often progresses in surprising ways, and technologies are frequently and quickly cross-applied between different fields. For example: stationary steam engines originated for clearing water from mines, but were quickly repurposed to give us the steam ships and steam trains of the Industrial Revolution. Similarly, we find a host of relevant technologies making rapid progress in fields entirely unrelated to geoengineering, which potentially offer surprising revisions in the cost estimates and technology choices from previous reports.

To summarise the key conclusions of the Aurora and NAS reports, the findings were generally favourable to aircraft as an injection platform technology, while Davidson found tethered aerostats substantially cheaper. While less-familiar approaches were considered in varying degrees of detail, these typically had practical and/or costs issues associated. For example, Davidson dismisses aerosol delivery using 20 km-tall towers as being both entirely impractical and impossibly expensive. The use of aircraft is inherently advantageous from an engineering point of view—as, when compared to various other possible approaches (such as railguns and towers) aircraft are a well-developed technology, albeit with a requirement to optimise for the unusual use case. Moriyama's reanalysis noted convergence on costs estimates for existing technologies—and, by contrast, deviation on more novel ones. This emphasises the difficulty of appraising multiple novel technologies in a single report.

Part of the issue in performing the analysis offered by Aurora and NAS is that the expertise brought to bear is a function of that available in the market. Aircraft engineers are readily available (Aurora being primarily flight engineering-focussed), while coilgun engineers are far harder to find. Nevertheless, in the intervening years, technology has marched onwards substantially. It is therefore appropriate to review all of the key technologies discussed in the reports, and offer some brief comments on their capabilities—as reflected in the current state of the art of engineering in 2020.

Before considering the technical progress, a mention is merited of the state-of-the-art in atmospheric science. Recent work still posits approximately a 20–25k injection altitude [9] (minimum 20 km, optimally 25 km or more), albeit no longer with reliance on equatorial injection into the rising leg of the Brewer-Dobson circulation for transport [10]. Still greater altitudes are potentially an option, which must accordingly not be disregarded. The general current preference for multiple non-equatorial injection loci means that methodologies with flexible loci of deployment are favoured [11]—notably not favouring single-point solutions, such as towers or tethered aerostats—although the latter can be fitted to ships.

In addition to altitude and latitude(s), another factor with potentially significant implications for lofting requirements is the aerosol and method of dispersal. Injecting a gaseous precursor such as SO_2 is possible; this then oxidizes and forms sulfate aerosols—similarly to large volcanic eruptions, which serve as a natural analogue. Precursor injection likely does not require any loiter time at altitude. However, particularly at the higher injection rates needed to achieve greater cooling, direct injection of sulfate aerosols appears likely to have significant advantages [12, 13], but would require gradual dispersal and therefore loiter time at altitude. The same would be true if an alternate aerosol material such as calcite [14] were used. There are still large uncertainties with these alternate strategies, but lofting technology needs to be evaluated recognizing the potential value in loiter time at altitude.

Guns

In recent years there has been substantial progress in gunnery, and a range of novel technologies have come to the fore—although not all have survived the research and development winnowing process.

In general, a disadvantage of guns for this purpose is that they are poorly-suited to direct aerosol distribution —a process which may offer advantages [15]. Aerosol distribution is more challenging than to burst a shell full of precursors at altitude, relying on nature to turn these into aerosols. The resulting inherent challenge for gunnery is therefore twofold. Firstly, shells' short flight path tends not to provide the steady-state conditions needed for plume-type direct distribution—although hypersonic projectiles or gun launched gliders [16] can potentially address this limitation. Secondly, potentially-complex machinery needed for a direct distribution approach is challenging to engineer so robustly as to operate reliably after being fired from a conventional artillery piece. Guns therefore are now starting on the back foot, and it is likely that low-g, level-flight technologies will thus be favoured.

Fortunately, new gun technologies tend to have much flatter g/time curves than do conventional chemical guns—and potentially a higher muzzle velocity, which can give a flatter trajectory, without compromising altitude.

Gas guns

Conventional guns rely on a solid propellant. This is expensive, and its high density serves to concentrate the acceleration towards the early part of the shell's in-barrel journey. By contrast, gas guns work more like a car's cylinder—albeit with an enlarged chamber. This gives both a smoother acceleration, and a far cheaper propellant (e.g. methane). The now-defunct Utron [17] developed gas guns for military use, and the similarly-failed Quicklaunch [18] proposed the same approach for orbital access, using a light gas gun (light gases having higher sonic speeds, and hence higher potential muzzle velocity) [19]. A comparable technology to the light gas gun, albeit with a fundamentally different design, is the ram accelerator—currently being commercialised by Hypersciences [20]. Propellant is a key cost constraint on conventional guns; propellant cost being approximately half of the total cost for the gun-based delivery, as considered by Aurora. For military use, where firing frequency is low, propellant cost is relatively trivial (as a component of overall costs). As such, little attention has been given to this aspect of gunnery—perhaps one reason why gas gun development has been limited.

Around half of the cost of guns considered by Aurora were made up of the cost of non-recoverable shells. The original reports did not investigate the opportunity to recover shell casings for reuse. Intuitively, a shell that can be accelerated intact with the length of a gun barrel can also be decelerated within a comparable distance. One way to recover shells is to splash them down into water, using nets or hoppers to recover the spent casings for refurbishment, refilling and reuse. Unguided shells are already accurate enough for collection. Accuracy may be further improved by guidance systems [21]—albeit with cost and potential survivability issues, as guidance fins are a relatively delicate and expensive component. Shell recovery again removes a very large fraction of the costs—but experimentation is necessary to determine whether the shells can indeed be recovered and reused, without significant refurbishment. If this can be achieved (along with gas conversions), the cost of gun systems could be reduced by around one order of magnitude from the costs presented in the Aurora report. However, the low level of investment in the wider field of novel combustion gunnery is a limitation to the applicability of gas gun technology to geoengineering—as all the engineering risk is loaded into geoengineering, not supporting industries.

Notably, the Aurora report envisaged a far greater payload for shells than was available with the current generation of technology. This is one aspect where progress is perhaps less promising. The limitations of in-flight ballistics favour the use of short, stubby shells for gyroscopic stability. Long, needle-like shells tend to tumble in-flight—rendering them dangerously uncontrollable [22]. This mode of failure was seemingly not considered in depth by Aurora, when they suggested a much higher-capacity shell—something that can only be achieved with thinner casings (which are already close to their strength limits, for solid propellant) and more elongated shells. A further complication is that fluid payloads do not spin-up perfectly, again reducing gyroscopic stability (another factor ignored by the Aurora report). One approach to dealing with these challenges is the use of fin-stabilized projectiles. Projectiles with fixed fins can be launched from guns that rely on discarding sabots, and thus over-calibre barrels—a design commonly used for anti-armour purposes. However, this approach requires a considerable engineering adjustment to the technology envisaged in the Aurora report—with either oversized barrels or comparatively small projectiles. By contrast, folding fins do not require barrel amendments. A US program to develop a carbon fibre lightweight high capacity projectile shows that developments in this field are indeed possible [23, 24]. However, such an approach does not necessarily mesh with the need to provide a cheap, recoverable shell casing; fins are likely to be torn off, on splashdown. Further, these carbon-fibre shells may be generally prone to damage on landing, which may not permit reuse.

In summary, gas guns may be far cheaper (perhaps one tenth the cost) than the conventional guns envisaged by the Aurora report, but are inherently less suitable for direct distribution than non-ballistic, level-flight technologies. This possible price advantage over conventional guns does not overcome the relative advantages of similarly-priced aircraft, for direct aerosol injection. It is unlikely that chemical guns will be the preferred technology, should the current expectation of superior performance for direct aerosol injection persist. Nevertheless, light gas guns are particularly suited to high-altitude access.

Railgun

Railgun technology development has continued apace since publication of the reports [25]. However, the applicability of this approach to geoengineering remains highly questionable. The key concern with railgun technology is the issue of wear. Very high muzzle velocities are achievable, but direct contact between the projectile and rail is required, meaning that wear is inherent in the system design. Even with advances seen in recent years, it is unlikely that it could be readily adapted for geoengineering use—as component life is only of the order of 400–1000 shots. Nevertheless, the electrical energy source, and high altitude accessible (rail gun technology is hypersonic), mean this technology may yet find a geoengineering role. If the rails can readily be refurbished or replaced, or some technological approach found to reduce wear, then the principal limitation of the railgun will be overcome. However, there is, as yet, set no sign of this happening.

Coil guns/MAGLEV

An alternative gun technology is the coil gun. This relies on a different electromagnetic effect from the railgun, and friction contact is not a prerequisite. This is, to some extent, related to the concept of a MAGLEV train—a technology that has experienced a remarkable revival of interest, during the quiet period. Not only are high-speed MAGLEV systems already built, but a more directly-applicable version is to be found in the sonic-speed Hyperloop concept [26]. Resurgence of long-dormant vactrain technologies have led to a renaissance for interest in electromagnetically-accelerated transport systems. Serious proposals are now in place in a number of countries, notably in the developing world (e.g. from DGW Hyperloop and Hyperloop Transportation Technologies), to bring forward this magnetically-accelerated evacuated tube technology as a mass transport system. Unlike the trains and monorails conventionally associated with the MAGLEV approach, Mach speeds are inherent in the intended designs. This is useful for geoengineers, as it offers an electrically-powered, near-term technology capable of speeds that are a large fraction of those necessary for geoengineering use. Nevertheless, substantial modifications would be required to adapt hyperloop for geoengineering use. As well as a significant speed increase, track would have to be installed that was steep or vertical, for a considerable length. If the track changed gradient, like a ski jump, a high-radius curve would be needed to reduce *g* forces. An alternative would be to launch a supersonic glider, which would transition to vertical motion aerodynamically—but this poses a number of significant engineering challenges regarding drag forces, energy loss, and tube dimensions.

Previously, the use of electromagnetic approaches has been considered for space launch [27]. Key challenges to the use of vacuum tubes obviously include the need for release—thus opening and closing the tube, so as to allow the passage of the projectile whilst maintaining a relatively good vacuum. This is not an inherent feature of Hyperloop—and, unless the system gets used for other launch types, geoengineers will have to do the development themselves. Alternatively, the same approach could be used with an open track MAGLEV system. This amendment obviously removes the need for engineering of the tube termination—but it creates additional problems in terms of aerodynamics, with aerodynamic heating and stability problems potentially inherent. Furthermore, the transition between on-track and off-track aerodynamics is non-trivial. This issue requires careful consideration, to ensure the survivability of the projectile—particularly if it is intended to have orderly flight characteristics, to achieve similarly-orderly dispersal.

A possible solution to the transfer between track and ballistic motion is to launch a projectile using a fixed sled, which does not leave the track—instead braking, to release the projectile. This would have the additional advantage of removing the need for expensive and heavy electrical or magnetic components on the projectile. It would, in essence, function similarly to the catapult launchers common on aircraft carriers. Notably, either a ballistic or gliding design for the projectile is possible. This latter concept is similar to Aurora's rocket-glider approach. Coilgun or MAGLEV launch accelerations may be modest, easing design issues. Limitations imposed by the tube diameter, plus the need to minimise drag, mean that wings may have to be deployed at apogee. The economics of reuse are likely to be overwhelming; we assume at least an order of magnitude difference between reusable and disposable projectiles. Accordingly, we envisage a parachute or gliding recovery; the larger and less robust hyperloop-type vehicles would be unlikely to survive the marine splashdown suggested for chemically-propelled gun shells.

Finally, any track-based design tends to favour a fixed injection locus—unless mounted on a very large ship or terrestrial turntable, neither of which presently exists. Therefore, local injection saturation needs to be considered. Steerable projectiles offer one possible, partial solution—and very high-speed launches offer limited additional flexibility over injection locus, at the cost of engineering the system for much higher speeds. Once all the above issues are considered, the resulting projectile begins to look more and more like an aircraft—losing many of the inherent advantage of electro-magnetic launch. Nevertheless, at large and uncertain development cost, a sled-launched supersonic glider could conceivably have cost advantages: the inexpensive energy source (electricity) and lack of weight and drag from engines and fuel tanks mean that such gliders have inherent advantages over powered aircraft.

The feasibility of this approach may be largely set by the fortunes of Hyperloop companies.

Tethered balloons

The use of static balloons has been considered but has never found favour as a primary method, save in Davidson's work. The technology has not been developed rapidly, in the quiet period. The development work that has taken place has been entirely specific to geoengineering use. The ill-fated SPICE project [28] was by far the most serious attempt to engineer tethered balloon technology for geoengineering application. The test process was a failure [29], on engineering, project management, and public relations grounds. The controversial tests were shelved—as a result of both public protest and hose damage (from mishandling). Notwithstanding the difficulties of engineering this technology, the fundamentals of using a tethered aerostat for geoengineering have proved to be more complex than was at first envisaged. The issues related to pressure (up to 4000 bar) and temperature of a carrier fluid mean that the choice of transport slurries and particles is limited [4]. The drag force acting on the tether in high winds (e.g. in the jet stream) and also the potential for instability resulting from vortex-shedding adds complexity to the tether design. Managing these issues requires specific engineering treatment, such as potentially requiring a non-circular streamlined cross-section. The tether (which is also a high-pressure pipeline) would need to be made from a fibre-reinforced material, with strengths at the limit of today's technology. However, the manufacturing capability for tethers and pipelines exists only for short lengths. A tether/pipeline of 20 km in length is challenging—especially as it would need to be made in one piece, to avoid the complexity and weight of joints. As for aerostat design, each tether will be supported by a single hydrogen-filled (or helium, if available) balloon. This is likely to be hundreds of metres in diameter—larger than the largest of football stadiums, possibly including the car park. No balloon of this size has ever been manufactured or launched. Launching a *tethered* balloon is far more difficult than a free balloon, adding to the complexity. The end result is that the practical difficulties of creating a suitable tethered aerostat are only amplified by the more fundamental engineering issues of pumping particles or precursors up a pipe—independent of how that pipe is supported. Nevertheless, Davidson remains bullish on costs. However, the immaturity of the technology, and the lack of parallel development for other types of use, render such cost estimates highly speculative—as the secondary review emphasised. Finally, the challenges of reaching optimal altitude, the inflexible locus of injection (unless ship-mounted), and the inherent lack of redundancy all serve to weaken the case for this technology—even if the considerable engineering challenges are surmountable.

Free balloons

Balloon technology has developed somewhat in the quiet period. Firms such as Google (Alphabet) [30] have developed long-endurance balloon platforms, intended to distribute internet access to remote areas. The altitudes planned approach those applicable to geoengineering use, meaning the technology is superficially promising. However, the use of this approach for transport has not received comparable focus, and there is also still no clear evidence that balloon platform use is set to become widespread [31]—especially as satellites, such as Starlink, begin to fulfil a similar role. Accordingly, there is no reason to move them from their less-favoured status, according to Aurora. What is notable, however, is research suggesting the potential use of mass-produced weather balloons by the public [32]. Although not necessarily cost-effective for scaled use, the principal impact of such a public participation project would be political. Therefore, the use of balloons may be likely on accessibility grounds, rather than on their engineering or cost merits. Nevertheless, if recoverable balloons could be made cost effectively, using modest modifications to the weather balloons proposed, then this low-tech approach may ultimately turn out to be effective. Without a means of recovery and reuse, these comparatively cheap balloons will likely only be useful for political leverage, as they suffer from inherent issues of litter and cost (four times that of aircraft). Additionally, all such balloons cause the pollution of the stratosphere with lifting gas (hydrogen), or the loss of irreplaceable gas into space (helium); at scale, this is a non-trivial problem.

Airships

Hybrid airships were received favourably in the Aurora report. This technology relies on a marginally heavier-than-air vehicle—which is held aloft by aerodynamic lift, as a result of its body shape. The buoyancy of a lifting gas (typically helium), means that the aircraft does not have all the inherent challenges of lift in rarefied air that conventional fixed wing aircraft experience. As a result, this technology remains promising for geoengineering investigation. Developments from Hybrid Air Vehicles [33, 34] show serious engineering effort invested into non-geoengineering uses of this technology—vastly simplifying the task remaining for geoengineers. Another firm active in this sector is Flying Whales [35], a conventional airship firm.

Although remaining a relatively niche approach to air transport, the airship industry is nevertheless redeveloping rapidly, after a long hiatus—and thus remains a promising candidate for future repurposing to the geoengineering use case. However, the required high-altitude application of this technology has yet to be forthcoming, with an altitude of around 6 km claimed, but only 1 km tested so far [36]. It is unclear whether high-altitude use cases, such as surveillance, will be fulfilled. The nascent status of this technology, together with the ongoing doubts about its future development for high-altitude use, mean that at it must be considered much more speculative than the iteration of fixed-wing aircraft designs.

A more radical approach is a postulated new generation of vacuum airships [37]. These overcome restrictions on the availability of Helium, using an empty, rigid-walled chamber. Whilst the original idea dates back centuries [38], only recently have the necessary advances in materials been made to facilitate the development of such aircraft (e.g. by O-boot [39]. With no difficulty in adjusting ballast, no obvious limits to materials supply, claimed high operating ceiling, and unlimited dwell time, these craft have a number of advantages. Due to the peak crush loads for such craft being at the lowest altitudes, they may be restricted to operating from mountain landing areas or very tall mooring masts.

Aircraft

The use of aircraft was favoured by the Aurora report. The advantages of a very large field of both suppliers and experts means that aircraft technology is well understood and well-exploited. Although heavy-lift aircraft capable of flying to the stratosphere have not yet been developed, planes of sufficient size, and separately of sufficient altitude capability, have flown extensively. Thus, designing a geoengineering aircraft should not be particularly problematic—unless higher altitude access (e.g. 25 km) is seen as worthwhile. The results of the analysis done by Aurora suggested that costs were lowest with a new aircraft design. In the medium term, adaptations to small executive jets were envisaged—but later analysis has shown that these are unachievable, as the capabilities of existing aircraft are fundamentally unsuited to the operational ceilings required [6].

A team at the Technical University of Delft [40] has done a reasonably-thorough engineering investigation of the designs required for a geoengineering aircraft. Their chosen approach was to create a large, slow moving, powerful, high-lift aircraft—with a passing resemblance to the ill-fated Spruce Goose seaplane [41]. An alternative design study has also recently been conducted [42]; this more closely resembles a conventional tanker, such as the KC-135 or KC-10. Both of these aircraft are designed to deliver aerosols at roughly 20 km, with the sustained level-flight capability needed for direct aerosol injection. There are potentially significant aerosol lifetime and radiative-forcing benefit to higher altitude injection—but generating both sufficient lift and sufficient thrust becomes much more challenging at altitude—as both scale with air density, which drops by roughly a factor of two between 20 and 25 km.

The clear advance in aircraft technology during the quiet period has not been in aerodynamics or propulsion—but instead has been focused almost entirely on automation and control. Drones are now used ubiquitously by the military, and are increasingly creeping into civilian commercial use. Eventually, this trend towards automation will encompass larger aircraft, but it presently concerns small quadcopters, etc, which bear little resemblance to geoengineering aircraft. Nevertheless, in coming years it is almost inevitable that partially or fully autonomous drone technology will be used for heavy civilian aircraft. By nature, geoengineering flights are repetitive, tedious, and isolated from other traffic. They are thus well-suited to machines rather than humans. The Delft study envisaged pilotless drones, accordingly.

As regards power systems, the key development has been in the field of hybrid engines. Through its partner Reaction Engines, BAE Systems have put considerable engineering effort into developing the Synergistic Air-Breathing Rocket Engine (SABRE) hybrid rocket/jet engines for space launch [43], with a focus on suborbital planes. Development has continued throughout the quiet period, culminating in an European Space Agency stage greenlight [44]. This technology promises easy access to the high atmosphere. Should higher injection attitudes be needed, engines derived from this hybrid approach are likely to be a natural choice, overcoming problems that would otherwise be insurmountable with conventional propulsion. Additionally, the engines' hypersonic capabilities enable it to be used for zoom climbing, as well as for operation in thin air.

Finally, it merits a mention that while the energy-density today is not sufficient, battery-electric technology is progressing rapidly. Both incumbent (Nissan) and upstart (Tesla) vehicle manufacturers are investing heavily in

R&D for surface transport. The technology is additionally finding its way into the air, too [45]. As well as potentially overcoming altitude limitations for air-breathing engines, electric propulsion, potentially offers cost, environmental and maintenance advantages. The potential use of short, repetitive flight plans would be a good fit for battery technology—as it is inherently range-limited, due to energy-density issues. An electric plane could potentially piggyback on a conventionally powered plane, in order to get it to medium altitude, without draining its batteries. This piggy-back concept has been demonstrated by the White Knight 2 aircraft, from [46] Scaled Composites.

Rocketry

The field of rocketry has advanced extremely rapidly in recent years, led by companies such as SpaceX [47] and Blue Origin [48], as well as including more minor players such as Virgin Galactic [49]. The key innovation step in modern rocketry has been to recover the expensive first stage—leading to potential cost reductions of around an order of magnitude, once refurbishment has been systemised [50]. Further falls of similar order are conceivable, if rocketry becomes a mass-market technology—robustly challenging Smith and Wagner's assumptions of a 50x cost disadvantage. This scaling may well occur, if SpaceX's plans for sub-orbital passenger transport flights come to fruition [51]. Costs for any form of non-space cargo use are highly speculative, at this stage.

The Aurora flight report did envisage the use of recoverable rocket-powered gliders, finding them to be uncompetitive. It is unlikely, however, that these off-the-shelf rockets are fully cost-optimised. By contrast, SpaceX's relentless focus on costs will continue to lead to reductions in price, which were unimaginable at the time that the first report was written. Again, in common with hybrid jet/rocket engines, use of recoverable rockets will enable access to the high atmosphere—giving geoengineers great flexibility over injection altitude, and resulting materials-efficiency advantages. SpaceX's proven ability to land on barges also frees up the technology from the constraints of conventional spaceports—helping to address potential local saturation issues, as well as concerns over local hazards.

Towers

The use of free-standing towers was found generally to be impractical, when issues of costs, materials availability and development time were factored in. Nothing has occurred to change this, although there have been great advances in graphene technology. Nevertheless, this material remains at the very beginnings of commercial usefulness—albeit showing great promise. As such, it is only a *speculative* technology to improve costs and performance of another technology—which is itself very speculative. A major component in the design of a tower is its resistance to wind loading. At 20 km in height the tower will, from time to time, be subject to the high wind speeds of the jet stream. Wind loading is a dominant factor in the design of the tallest buildings in the world today, but these do not experience winds anything like as ferocious as in the jet stream. For any realistic near-term analysis, towers remain entirely implausible.

Conclusions

The quiet period has resulted in a notable jostling between the technologies. Key updates are summarised below:

Aircraft remain the leading technology, in the medium term. This is despite the apparent implausibility of retrofit projects to convert existing platforms. A custom design seems inevitable, for any serious use. Unconventional propulsion advances (hybrid engines, electric planes) may unlock useful increases in operational ceiling, but do not look to be crucial to deployment. Lofting costs have been estimated to be approximately $1000–1500 per ton, giving an overall cost measured in billions of dollars per year.

Rockets have advanced fastest, in terms of fundamental costs (and thus likely usefulness). Nevertheless, any applicability to geoengineering remains largely speculative—and their principle advantage, of an unlimited high operational ceiling, may be unnecessary. Medium-term cost competitiveness with conventional aircraft is also speculative, to say the least. It is likely to be one to two decades before clarity on costs for suborbital use is obtained. Scaling from existing costs is prone to large inaccuracies.

Gas guns benefit from fundamentally-better economics than other chemical guns. A simple analysis shows the potential for a nearly one-order cost reduction in shot costs—by eliminating costly propellants, and recovering shells. However, early progress on the technology has stalled. Despite their altitude advantages, it is unclear whether there is any strategic reason to adopt gas guns, considering the difficulties of engineering complex distribution systems for direct distribution of particles. Even the lower acceleration of gas guns is still far higher than that of coilgun/MAGLEV technologies. Nevertheless, light gas guns remain an option for very high altitude access.

Railguns have made major advances, but remain non-viable. Future development may make them useful - but likely only for extreme altitudes, due to their inherent wear (and thus cost) limitations.

Coilguns/MAGLEV technologies have benefitted from rapid non-geoengineering development—particularly by the various firms developing Hyperloop. Despite this, Hyperloop remains embryonic, and there have been no known attempts at engineering any versions for launch use. Inflexible track positioning, and projectile design issues, pose potentially-strategic obstacles to geoengineering use—as do complexities surrounding the potential use of vacuum tubes. There appear to be no overwhelming technical benefits to using this method for lower altitudes, and reengineering for launch use is highly speculative. Nevertheless, repurposing hyperloop technologies to launch supersonic gliders from sleds may ultimately be plausible, and has inherent cost and payload advantages over conventionally-powered flight.

Free balloons: despite commercial deployment advances, no major technical or scaling progress has occurred that would imply a major shift in costs for recoverable balloons. Single-use free balloons have their own issues: litter, and lifting gas rejection. Single use balloons therefore remains an unattractive technology for scaling. However, the DIY nature of geoengineering using off-the-shelf balloons means that early deployment is feasible, even if later scaling is not.

Hybrid and vacuum airships have developed steadily, realising some of the promise assumed by Aurora. Although a nascent technology, they remain a serious alternative to conventional aircraft. Further development for non-geoengineering uses is likely to be essential, if these are to ultimately overtake fixed wing aircraft for relevant use-cases—with high-altitude versions of particular importance.

Tethered balloons: progress has been slow, as non-geoengineering uses appear not to be actively pursued. Major challenges are inherent in pipe material, manufacture, transport, and balloon size. It is not clear if such a system can ever be viable.

Towers: remain entirely impractical, with no medium-term breakthroughs expected.

In summary: a new generation of aircraft remains the most likely option at scale, potentially with unconventional propulsion. However, hybrid airships are a credible challenger. Both of these types of platforms benefit from the ability to carry out stable, level flight.

Rockets and MAGLEV/coilguns are promising outsiders, due to rapid independent development—with gas guns also promising in principle, but lacking current development progress. None of these approaches are naturally optimised for stable, level flight—which is optimal for aerosol direct distribution. Nevertheless, the relatively low-g launches of rockets and MAGLEV (compared to guns) make them inherently suitable for launching gliders.

Should very high-altitude access be required, light gas guns, rockets, and rocket-hybrid powered aircraft are useful standby technology alternatives. Railguns have inherent disadvantages, but cannot be comprehensively ruled out, for extreme altitudes.

Tethered balloons have only an outside chance of success, suffering with highly uncertain costs and performance—and no independent development. Free balloons are a wildcard technology, which facilitate early and rogue deployment, due to their near-zero capital costs.

We discount towers.

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